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DIRECTED PROJECTION OF A BODY BY THE

PRODUCTS OF AN EXPLOSION

Translated by

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ABSTRACT. This report is a translation from the <u>Zhurnal</u>
<u>Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki</u> on a subject
that is of interest to warhead design and research. The
motion of thin discs and shallow cones that are projected
by the central initiation of a layer of explosive is
investigted by a one-dimensional theory and compared to
experimental data.

U.S. NAVAL ORDNANCE TEST STATION

China Lake, California   March 1966

FOREWORD

The text of this report was translated from a Russian journal at a time that no regularly scheduled translations were made. The article discusses results of Soviet research that have a direct bearing on the understanding of the principles of warhead operation and design. Four other translations of Russian articles were made to assist research and design workers in the warhead field: NAVWEPS Report 9043, NAVWEPS Report 9044, NAVWEPS Report 9045, and NAVWEPS Report 9046.

This article "Directed Projection of a Body by the Products of an Explosion," by G. M. Lyakhov was published in Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, 1962, No. 3, pp. 44-52.

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DIRECTED PROJECTION OF A BODY BY THE PRODUCTS OF AN EXPLOSION

by

G. M. Lyakhov

In the explosion of a charge of H.E. that has on its surface a deep cavity covered by a thin metal liner, a collapse of the liner occurs with the formation of a jet and slug. The phenomena of shaped charges are studied in the works of Ref. 1-3.

A hydrodynamic theory of shaped charges that allows the establishment of quantitative relations between the parameters of the charge, the characteristics of the jet and its armor-piercing action has been worked out by M. A. Lavrentev (Ref. 4).

Below are presented the results of an investigation of the explosion of charges with small thickness of the cavity. It is established that in this case the liner is turned inside out and it fails with the formation of a directed flow of its elements. Experimentally investigated motions of these elements have determined the conditions under which the theory of one-dimensional motions can be applied to the directed projection of these elements. One-sided and two-sided projection is considered. A quantitative relation between the parameters of the charge and the characteristics of the flow is determined.

1. An Investigation of the Mechanism of the Explosion and the Determination of the Initial Premises of the Calculation

Directed projection may be realized by means of charges of various shapes, for example, plane (Fig. 1a). A charge with concave shape and having a thickness of the layer 1 of H.E. much less than the radius R is the most convenient in the utilization of energy (Fig. 1b).

In order to devise a calculation procedure it is necessary to have data on the mechanism of explosion of such charges. An investigation was carried out by means of instantaneous X-ray records of the explosion of charges which had a liner on the concave side but the back and lateral sides were free.

The X-ray records were taken over 30-40 μsec intervals with an interval between radiographs of 2-5 μsec.
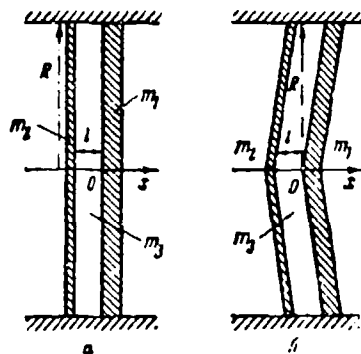
FIG. 1.

The method of synchronizing the record and the explosion allowed the determination of the moment of time corresponding to each radiogram to an accuracy of 2 μsec.

In Fig. 2-8 are given the radiograms representing the charge during the explosion and at moments of time equal to 2, 4, 15, 25, and 30 μsec. The calculation of time was carried out from the moment of the initiation of the explosion. The mass of the charge of H.E. (trotil) is 8.5 g, the mass of the liner (tin) is 3.14 g, D--is an immobile rod with respect of which displacement is measured.

In the first moment of time the central part of the liner is already involved in the motion (Fig. 3). The front of the detonation wave still has not reached the lateral (free) surface of the charge; the elements of the liner bordering on it are still at rest. The products of detonation are flying off from the lateral surfaces.

At the moment of time t = 4 μsec (Fig. 4), all the elements of the liner are shown to be involved in the motion. The central part, which the detonation wave had reached the earliest of all, outruns the lateral elements, as a result an inversion of the liner occurs and it acquires the shape of a plane disc. The radius of the base of the disc does not grow, consequently it undergoes in this period a compression in the direction perpendicular to the axis of symmetry of the charge and from this surface the products of detonation begin to fly out.

Figure 5 corresponds to the complete inversion of the liner. The height of the cone which is formed by the deformation of the liner exceeds its height before the explosion. This shows that after the compression an extension of the liner occurs.

From Fig. 6-8 it can be seen that in the further motion the velocity of the central and lateral elements of the liner remain different which produces in it further extension and rupture into fragments. From this
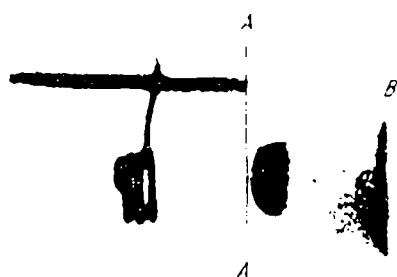
FIG. 2.
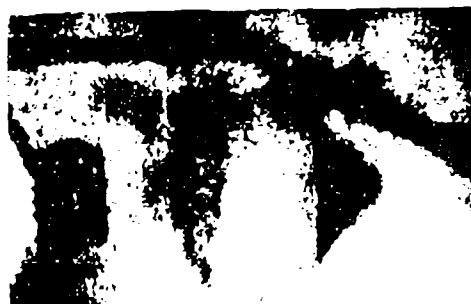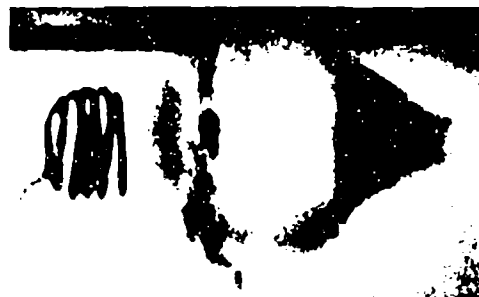

FIG. 3.

FIG. 4.

FIG. 5.

FIG. 6.

FIG. 7.

FIG. 8.

time the distance between the fragments grows. The velocities of the
fragments have a component in the direction of the axis of symmetry and
in the perpendicular direction. There is insignificant breakthrough of
the gaseous products of detonation. The expansion of the products of
detonation continues, spreading from the free surface. The front of these
acquires a spherical form.

In Fig. 9 is presented the results of measurements of the displacement
of the central (1) and the lateral (2) elements of the liner. The experi-
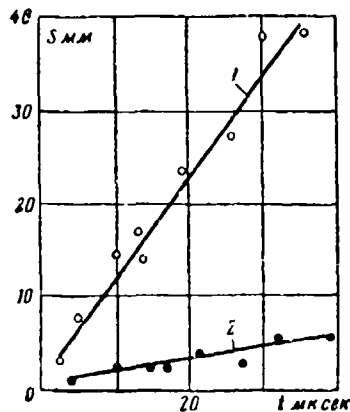mental points are taken from the radiograms in Fig. 2-8.

FIG. 9.

From the results of the experiments it follows that the velocity of
the elements of the liner grow to a maximum (limiting) value less than
that for 2-4 μsec and then during the investigated span of time
(30-40 μsec) remain constant. From this it follows, that in the parts of
the path which have been traversed to this time, there is little effect
from the resistance of the air; even moreso the air resistance need not
be taken into account in the period of accelerated motion of the liner.

The experiments show that the various elements of the liner enter into
the motion at various moments of time. The motion of the lateral points
starts later than the central parts that are connected with the continua-
tion of the detonation wave by the H.E. The limiting velocity of the
various elements is different. The central elements have the maximum
value (1,100-1,200 m/sec), and the lateral elements the minimum (120-150).
This difference is explained by the effect of the outflow of the products
of explosion from the lateral surfaces of the charge. A relief wave
formed in this way moves to the center of the charge and leads to a drop
in the pressure and, consequently, to a lessening of the acceleration of
the corresponding elements of the liner. The closer the element is to
the center of the charge the higher the velocity it has time to acquire.

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For a sufficiently large charge radius R compared to the thickness ℓ, there is no influence of the relief on the velocity of the central elements since these acquire the limiting velocity upon the arrival of the front of this wave.

The experiments show that in the compression inversion and extension of the liner an interchange of velocities does not occur; these maintain the velocities that were acquired in the period of accelerated motion.

In the propagation of the detonation wave from the axis to the lateral surface, the angle of its approach to the elements of the liner diminishes. For $R \gg \ell$ and for the majority of the elements it may be assumed that the wave moves along the liner, calling for a simultaneous detonation of the H.E. over the whole space between the liner and the back surface of the charge. The motion of the elements may be determined by a scheme of instantaneous detonation.

The experiments that were carried out allow the investigating of the mechanism of the explosion of a charge and the substantiating of the physical hypothesis of its calculation.

1. The hypothesis of M. A. Lavrentev, stated by him for the case of shaped charges, is applied to the directed projection; the strength and the plastic forces that are developed in the material of the liner during its deformation in the period of acceleration are small compared to the inertial forces. The material of the liner may be considered as an ideal incompressible fluid.

2. In a charge of sufficiently large diameter (compared to its thickness) the motion of the central elements may be considered without the calculation of the influence of the relief wave running from the lateral surface.

3. The detonation in sections found at various distances from the axis of the charge occurs at various moments of time, but in each section it is simultaneous.

4. In the period of accelerated motion of the liner, the resistance of the air may be neglected.

2. The Calculation of the Motion of the Elements During One-Dimensional Projection

In accordance with the assumptions that have been made, the central part of the investigated charges is considered as the aggregate of identical elements consisting of the layer of H.E. and the two (or one) hurling discs. The motion of the discs goes on in each of the elements independently as the result of the instantaneous detonation of the H.E. to be found in each element.

The one-dimensional, one-sided projection has been considered by K. P. Stanyukovich (Ref. 3) when the detonation wave approaches normal to the element and the second end of the charge is free. The scheme that has been adopted differs from the scheme of K. P. Stanyukovich in the assumptions about the nature of the detonation and, furthermore, in that one-dimensional and two-sided projection is considered.

We consider the motion of the disc in the case of instantaneous detonation of an element of the charge. We designate the mass of the discs and of the charge of H.E. (Fig. 1a and 1b) falling on unit cross section correspondingly m_1, m_2, m_3 and the density, speed of sound, and the pressure of detonation product at the first instant of time by ρ_0, c_0, p_0. As the origin of coordinates, we take the point of contact of the disc m_1 and the charge H.E. The motion of the disc takes place without resistance of the medium, i.e., in vacuum.

At the moment of time $t = 0$, an instantaneous detonation of the charge takes place and motion of both discs begins. Relief waves travel from these discs to the center of the charge which are determined by special (Riemannian) solutions of the fundamental equations of gas dynamics (the regions 1 and 1' in Fig. 10). The solution in the region 1 has the form

$$x = (u - c)t + F(u)$$

$$u + \frac{2c}{\gamma - 1} = \text{const.} \qquad (2.1)$$

Here and (in the following)

    u = the velocity of the particle
    c = the speed of sound
    γ = (the exponent of the isentrope of the products of detonation)

FIG. 10.

The function $F(u)$ and the constant are found from the boundary conditions. At the front of the relief wave $u = 0$ and $c = c_0$ therefore:

$$u + \frac{2c}{\gamma - 1} = \frac{2c_0}{\gamma - 1}$$

The velocity of the particles of gas adjoining the discs is equal to the velocity of the disc. The equation of its motion is:

$$m_1 \, du/dt = p$$

Using the equation of state of the products of the explosion in the form

$$p = p_0 \left(\frac{\rho}{\rho_0}\right)^{\gamma} \qquad \text{for } \gamma = 3 \qquad p = p_0 \left(\frac{c}{c_0}\right)^3 \tag{2.2}$$

Thus, since $u + c = c_0$ then $du/dt = -dc/dt$ and for $\gamma = 3$ we have

$$m_1 \frac{dc}{dt} = p_0 \left(\frac{c}{c_0}\right)^3 \qquad \text{or} \qquad c = c_0 \left(1 + \frac{2p_0 t}{m_1 c_0}\right)^{-\frac{1}{2}}$$

We define $m_3/p_0 = l$ (the length of the charge of H.E.) and $m_3/m_1 = \eta$ considering that $p_0 = 1/3 c_0^2 m_3/l$, we find

$$c = c_0 \left(\frac{3l}{2\eta c_0 t + 3l}\right)^{\frac{1}{2}}$$

From this we obtain the dependence on time of the velocity and the path x traversed by the disc in the region 1.

$$u = c_0 \left(1 - \sqrt{\frac{3l}{2\eta c_0 t + 3l}}\right),$$

$$x = c_0 t - \frac{\sqrt{3l}}{\eta} \left(\sqrt{2\eta c_0 t + 3l} - \sqrt{3l}\right) \tag{2.3}$$

Knowing u and x of the particles adjoining the disc we find in agreement with (2.1) $F(u) = m_1 c_0 u/p_0$ and the solution in the region 1

$$x = (u - c)t + \frac{m_1 c_0 u}{p_0}, \qquad u = c_0 - c \tag{2.4}$$

Analogously we obtain the solution in the region 1' in the form

$$x = (u + c)t + \frac{m_2 c_0 u}{p_0} - l, \qquad -u = c_0 - c \tag{2.5}$$

The velocities of the fronts of the waves are equal to c_0 therefore these meet at the point $x = -l/2$ for $t = l/2c_0$. As a result of the interaction of the relief waves region 2 will arise in which the flow is defined by the general solution to the fundamental equations

$$x = (u + c)t + F_1(u + c), \qquad x = (u - c)t + F_2(u - c) \qquad (2.6)$$

In the region 1 we have $u = (u - c + c_0)/2$; here on account of (2.4)

$$x = (u - c)t + \frac{m_1 c_0}{p_0} \frac{u - c + c_0}{2}$$

From the condition of continuity of u and c on the boundary of 1, 2 we obtain

$$F_2(u - c) = \frac{m_1 c_0}{p_0} \frac{u - c + c_0}{2}$$

Analogously from the condition on the boundary 1', 2 we define and we find a solution in the region 2 in the form

$$x = (u - c)t + \frac{m_1 c_0}{p_0} \frac{u - c + c_0}{2}$$

$$x = (u + c)t + \frac{m_2 c_0}{p_0} \frac{u + c - c_0}{2} \ell \qquad (2.7)$$

We designate the distance at which the boundary 1, 2 reaches the first disc by x_1 and the corresponding moment of time by t_1. Let the velocity of the disc become u_1, the speed of sound c_1, and the pressure acting in it p_1. Then from (2.3) and (2.7) it follows that

$$x_1 = \frac{\eta \ell}{6} \qquad t_1 = \frac{\eta + 6}{6 c_0} \ell, \qquad u_1 = \frac{\eta}{\eta + 3} c_0,$$

$$c_1 = \frac{3}{\eta + 3} c_0, \qquad p_1 = p_0 \left(\frac{3}{\eta + 3} \right)^3 \qquad (2.8)$$

The quantities t_1, x_1, u_1, c_1, p_1 do not depend on the presence of the disc on the second end of the charge. At $t = t_1$ the region 3 is formed in which the solution is determined by equations of the form of (2.6). From the condition of continuity of the junction of the regions 2 and 3, we find that in the region 3

$$x + \ell = (u + c)\left(t + \frac{m_2 c_0}{2 p_0} \right) - \frac{m_2 c_0^2}{2 p_0} \qquad (2.9)$$

The equation of motion of the disc in the region 3 is

$$p_0 \left(\frac{c}{c_0} \right)^3 = m_1 \frac{du}{dt}$$

Differentiating (2.9) we obtain

$$- \frac{du}{dt} = \frac{dc}{dt} + \frac{c}{t + m_2 c_0 / 2p_0}$$ (2.10)

Introducing successively the new variables

$$\tau = t + \frac{m_2 c_0}{2p_0}, \qquad c\tau = q$$

we obtain the equation of motion in the form

$$\frac{dq}{d\tau} + \frac{Aq^3}{x^2} = 0 \qquad \left(\frac{p_0}{m_1 c_0^3} = A \right)$$ (2.11)

Integrating (2.11) and taking the initial conditions into account, we find the velocity of sound in the layer of gas joining the disc, the velocity of the disc and the path passed over by it in the region 3 in the form

$$c = [2(B\tau - A)\tau]^{-\frac{1}{2}}$$

$$u = D - [2(B\tau - A)\tau]^{-\frac{1}{2}} - A^{-1}[2(B\tau - A)]^{\frac{1}{2}} \tau^{-\frac{1}{2}}$$

$$x = D\tau - \frac{[2(B\tau - A)\tau]^{\frac{1}{2}}}{A} - \frac{m_2 c_0^2}{2p_0} - \ell$$ (2.12)

Here

$$B = 2\eta\ell^{-2}(\eta + 9\lambda + 6)^{-1} + 2\ell^{-2}(\eta + 3)^2(\eta + 9\lambda + 6)^{-2}$$

$$D = c_0 \left[\frac{1 + 6(\eta + 3)}{\eta(\eta + 9\lambda + 6)} \right], \qquad \lambda = \frac{m_2}{m_3}, \qquad \eta = \frac{m_3}{m_1}$$

$$B = \left[\frac{2\eta}{\ell(\eta + 3)} \right]^2, \qquad D = \frac{\eta + 9}{\eta + 3}, \qquad m_1 = m_2$$

Inserting in the last of these expression (2.2) the velocity of sound (2.12) we determine the pressure acting on the disc.

Subsequently, there will occur many reflection of the waves from both discs. If both masses m_1 and m_2 are large compared to m_3 then the pressure in the products of explosion will be (only) slightly dependent on x and the further motion of the discs is determined from the assumption that $p = f(t)$.

We consider the case when the mass of one of the discs for example m_1 is less or equal to m_2 ($\eta \geq 1$). As is shown by the calculations which are carried out in accordance with (2.12) in this case the acceleration of the discs practically stops in the regions 3 and 3'. The velocity of the disc m_1 may be taken as the maximum in one of the moments of time t_2, of the corresponding region 3. The value of t_2 may be chosen for example from the condition of the intersection of the straight line

$$x = \frac{\eta}{\eta + 3} c_0 t - \frac{\eta \ell}{2(\eta + 3)}$$

corresponding to motion fro. the point x_1, t_1 with the velocity u_1, with the straight line

$$x = c_0 t - 2\ell$$

that is the boundary 3, 4 in the case when $m_2 = \infty$. This value of t_2 always lies in the region 3. We denote $x(t_2) = x_2$ then

$$t_2 = \frac{\eta + 4}{2c_0} \ell, \qquad x_2 = \frac{\eta \ell}{2} = 3x_1 \qquad (2.13)$$

The calculations show that for $\eta \geq 1$ the acceleration of the disc m_1 at t, close to t_2, is already insignificant and the velocity of it $u(t_2)$ may be taken as the limit velocity u^x.

The correctness of this assumption is verified by graphs of the velocity of the discs $u(t)$ (Fig. 11) and the pressure $p(t)$ acting on the disc (Fig. 12) which is constructed for $t \leq t_2$ according to (2.3) and (2.12) for the case of $m_1 = m_2$. For t close to t_2 the pressure becomes small and further acceleration of the discs may actually be neglected. In Fig. 11-15, c is the velocity of sound in the products of detonation at the first moment of time.

3. The Analysis of the Results of the Calculation

The expressions of the limit velocity of projection of the discs, that are determined from (2.12) for three cases of projection, when the masses of both discs are equal, the charge is bounded on the second side by an immovable obstacle, and the second plate is absent, have the form:

for $m_1 = m_2$

$$u^* = c_0 \left[\frac{\eta + 9}{\eta + 3} - \frac{\sqrt{3}(\eta + 3)}{\sqrt{(5\eta^2 + 18\eta + 9)(\eta^2 + 4\eta + 3)}} \right.$$

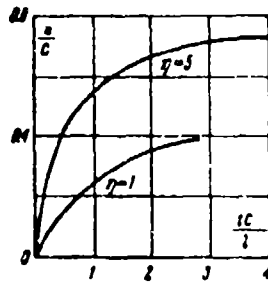$$\left. - \frac{2\sqrt{3}}{\eta + 3} \sqrt{\frac{5\eta^2 + 18\eta + 9}{\eta^2 + 4\eta + 3}} \right]$$
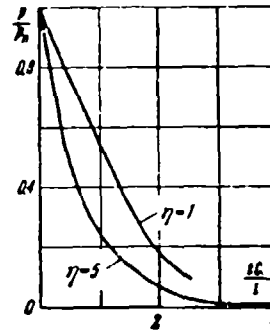
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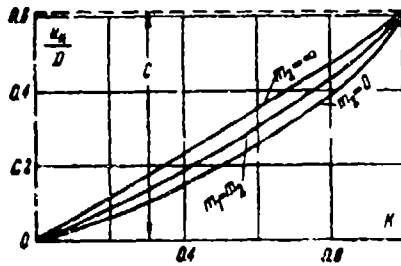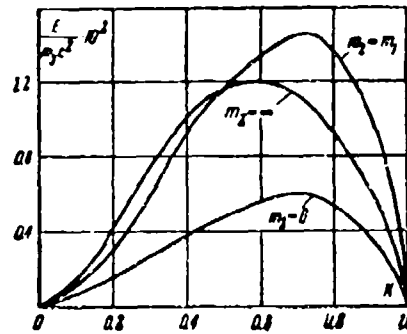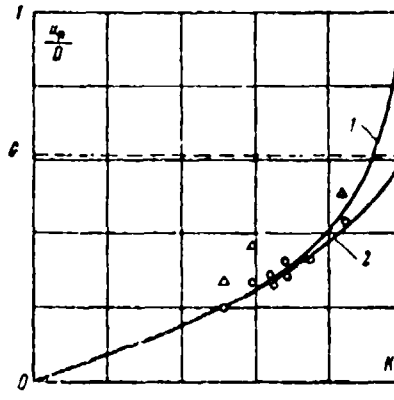
FIG. 11.

FIG. 12.

FIG. 13.

FIG. 14.

FIG. 15.

for $m_2 = \infty$

$$u^* = c_o \left[\frac{\eta + 18}{\eta + 6} - \frac{2\sqrt{3}(\eta + 6)}{\sqrt{(5\eta^2 + 36\eta + 36)(\eta^2 = 8\eta + 12)}} \right.$$

$$\left. - \frac{4\sqrt{3}}{\eta + 6} \sqrt{\frac{5\eta^2 + 36\eta + 36}{\eta^2 + 8\eta + 12}} \right]$$

for $m_2 = 0$

$$u^* = c_o \frac{\eta^2 + 12\eta + 18 - 6\sqrt{2\eta^2 + 16\eta + 9}}{(\eta + 6)\eta} \qquad (3.1)$$

In the conclusion of the second formula it is verified that in the case of the charge with mass of H.E. equal to $m_3/2$ and the projection of discs of mass m_1 bounded on the second side by an immovable wall, and in the case of a charge with mass m_3 bounded on both sides by discs of mass m_1 the velocities of the discs will be the same.

The last of the expressions corresponds to $t \to \infty$ since in this case the boundary 1', 2 does not catch up with the front of the products of detonation that are flying off to the left and the solution of (2.12) is correct for arbitrary t. We introduce the parameter

$$k = \frac{m_3}{m_1 + m_3} = \frac{\eta}{\eta + 1} \qquad (3.2)$$

In Fig. 13 is presented the dependence $u^*/D = f(k)$ constructed in agreement with (3.1) for the three cases of projection; D is the velocity of the front of the detonation wave. From the graphs it is seen that for $m_1 = 0$, $u^* = c_o$, i.e., equal to the velocity at which the products of detonation fly off in vacuum.

The presence of a disc of equal mass at the second end of the charge leads to the increase of the velocity of the first disc. The magnitude of the increase depends on the magnitude of k. The maximum increase takes place at $0.4 < k < 0.8$ and is greater than 10%.

The presence of a rigid barrier at the second end of the charge of H.E. leads to increase in the velocity of the first disc. The maximum increase occurs approximately in the same interval of values of k and amounts to close to 25%.

We find the value $k = k^*$ at which the kinetic energy of the discs has a maximum value for given mass m_3 of sum of the mass $m_3 + m_1$.

Figure 14 is given the dependence on k of the kinetic energy E that is attributed to m_3 and which has been constructed in agreement with the expression

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$$\frac{E}{m_3 c_o^2} = \frac{m_1 u^{*2}}{2m_3 c_o^2} = \frac{1-k}{k \ 0.61^2} \left(\frac{u^*}{D}\right)^2 \quad \text{for } m_2 = 0 \text{ or } m_2 = \infty$$

$$\frac{E}{m_3 c_o^2} = \frac{1-k}{k \ 0.61^2} \left(\frac{u^*}{D}\right)^2 \quad \text{for } m_1 = m_2 \tag{3.3}$$

From the graphs it follows that $E(k)$ has a maximum. The corresponding value of k^* is found either from the graph or from the condition that $dE/dk = 0$.

The optimal values of k^* in the three cases that have been considered are somewhat different. For $m_2 = 0$ the value of k^* is approximately equal to 0.75.

From the graphs of Fig. 14 it follows that if there is present at the second end of the charge either a disc or an immovable wall the energy of of the first disc increases. In the transition from one-sided projection to two-sided projection for $m_1 = m_2$ and $k = k^*$ the kinetic energy of both discs is approximately twice as great as the energy of one disc for one-sided projection.

Analogously differentiating the expression for the momentum of the disc J with respect to the mass of the charge of H.E.

$$\frac{J}{m_3} = \frac{m_1 u^*}{m_3} = (1-k)u^* \quad \text{for } m_2 = 0 \text{ or } m_2 = \infty$$

$$\frac{J}{m_3} = 2(1-k)u^* \quad \text{for } m_1 = m_2 \tag{3.4}$$

and equating the derivative to zero we find the optimum value of k^* at which the discs acquire the maximum momentum. At $m_2 = 0$ the value of k^* is approximately equal to 0.6. This value of k^* is not coincident with the optimum value from the energetic considerations. Thus, there are different values of the optimum value of k corresponding to maximum energy and maximum impulse.

The cases that have been considered apply to instantaneous detonations. If the detonation wave approaches normal to the disc then according to a solution by K. P. Stanyukovich in our notation

$$u^* = D \left[1 + \frac{27}{16 \eta} \left(1 - \sqrt{1 + \frac{32}{27} \eta} \right) \right] \tag{3.5}$$

where D is the velocity of the front of the detonation wave.

In Fig. 15 are presented graphs of $u*/D = f(k)$ for $m_2 = 0$. Curve 1 corresponds to Eq. (3.5), and curve 2 to Eq. (3.1). From the construction (it is found) that $c_o = 0.61 D$. For $k \leq 0.8$ i.e., form $m_1 \geq m_3/4$ both velocities are practically coincident. For $k > 0.8$ the wave that approaches normal to the disc attains the greatest velocity. The optimal value of k in both cases is practically coincident since $k < 0.8$.

Thus for discs of not too small masses the limiting velocity is determined by the amount of energy allotted in the explosion and by the ratio of the mass of the charge of H.E. to the disc and is practically independent of the point of initiation of the explosion and the direction of the approach of the detonation wave.

4. The Results of Experiments

We consider the results of experiments in the case of one-sided projection.

The motion of the disc corresponding to the case of the normal approach of the detonation wave to the disc may be approximately realized in experiments when the length l of the charge is much larger than its radius R. The initiation must be made on the axis of the charge from the end opposite to the projected body.

The motion of projected elements corresponding to the scheme of instantaneous detonation (Eq. (3.1)), may be obtained for $R \gg l$. In the initiation of the explosion on the axis, the detonation of elements that are at various separations from the axis does not occur simultaneously. In the case of a plane charge (Fig. 1a) this leads to the fragmenting of the liner before its elements acquire the limiting velocity. The detonation products burst through between the fragments and further acceleration of them is stopped.

In the case of a charge of convex form the breakthrough of the gases occurs more intensely so that it leads to a drop in the pressure and the stopping of the acceleration before the elements acquire the limiting velocity.

With a charge of concave shape, failure of the liner sets in later after it has been turned inside out. At this time the products of detonation have time to impart to the liner a velocity practically equal to the limiting velocity.

The velocity of the fragments may not reach the limiting value due to the effect of lateral relief waves. Taking the velocity of the front of the detonation wave as $D = c_o/0.61$ and the velocity of the front of the relief wave as c_o and knowing the time t_2 from formula (2.13) we find the distance R^o from the boundary of the charge at which the action of lateral relief waves does not have an effect on the velocity of the central fragments

$$\frac{R^O}{D} + \frac{R^O}{c_o} = t_2 = \frac{\eta + 4}{2c_o} \ell, \qquad R^O = \frac{\eta + 4}{2 \cdot 1.61} \ell \; . \qquad (4.1)$$

Thus for a charge with $R \gg \ell$, a correspondingly greater part of the fragments acquire the limiting velocity. These charges energetically become more advantageous.

The velocity of the fragments in the experiments was measured by mechanical methods, by the breaking of a series of frame targets set up along the path, and by optical methods by the speed of motion picture photography and by rotating film (photoscanning). Optical methods without illumination were applied only in the case of liners prepared from easily burned materials (such as alloys of aluminum).

Both optical methods gave approximately the same value of velocity which was different however from the results of measurement by mechanical methods. In direct proximity to the charge the optical methods fixed the velocity at 10-30% higher. However, with separation from the place of explosion these velocities quickly diminish and become less than the velocities that are determined from the breaking of the frame targets. Physically, this is explained in that the crushing of the liner forms various sized particles. As the results of measurement show, the middle- and large-sized particles from the main mass and these are approximately equal to the thickness of the liner before the explosion. Close to the charge, small particles that are brightly burning move first (these are formed as a basic consequence of the breakup); the velocity of these is determined by the optical method. As a consequence of the small mass these particles quickly lose velocity and in the section between the second and third frame target (the first was set up at the charge) the middle- and large-sized nonluminous particles have already caught up with these small particles.

A sample record of the motion of the luminous particles obtained by means of photoscanning is given in Fig. 16. The bright front propagating to the center of the circle corresponds to the motion of the front of the fragments. The products of detonation follow after these with less velocity.

In Fig. 15 the curves 1a and 2 are the limiting velocities corresponding to Eq. (3.5) and (3.1); the experimental values were obtained by the optical method (the triangles) and by the mechanical method (the circles). The charges were loaded with trotil. The experimental values correspond to the mean value of 5-6 experiments. The deviation of the results of the separate measurements from these values reached 10-20%.

From the comparison of the experimental values of velocity with curve 2 it follows that the great bulk of the fragments attain a velocity in satisfactory agreement with the theoretical calculation.

FIG. 16.

The experiments show that the limiting velocity of the fragments from charges with identical k but various m_1 and m_3, identical also, follow from the calculations. In further motion of the fragments of charges with small thicknesses of the discs these lose velocity very rapidly as the result of air resistance.

The velocity of fragments with $R < R^o$ in the experiments did not reach the limiting velocity $u*$. For $R = 0.75 R^o$ and for $R = 0.6 R^o$ these were respectively $0.96 u*$ and $0.42 u*$.

Experiments with charges having conical, spherical, parabolic, and other forms of cavity, showed that the velocity of the fragments in all cases were identical if $l \ll R$.

The isentropic exponent γ of the products of explosion was taken as three in the calculations. Actually for small pressures this exponent has a smaller value. The closeness of the experimental results and the calculation indicate that on the whole the acceleration of the disc occurs under large pressures when the value of γ is close to three.

Thus the presence on the surface of a charge of H.E. of a cavity of small depth bounded by a liner makes for the creation of a directed flow of its elements. If such a charge has in all sections parallel to the axis of symmetry a thickness of the layer of H.E. and liner that are equal then the velocity of projection of the elements may be calculated on the basis of the theory of one-dimensional motion.

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